# BIDIRECTIONAL REFLECTANCE MEASUREMENTS FROM SPACE WITH THE EOS MULTI-ANGLE IMAGING SPECTRORADIOMETER (MISR)

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## Abstract

The first spacecraft in the NASA Earth Observing System (EOS) series, EOS-AM1, is scheduled for launch in **June** 1998. The Multi-angle Imaging SpectroRadiometer (MISR) instrument is currently under development for flight on this platform. The instrument will obtain global multi-angle imagery at nine separate view angles oriented fore-aft along the spacecraft ground track, and will use a separate charge-coupled-device pushbroom camera at each angle,. MISR measurements will be used to retrieve the optical properties of tropospheric aerosols over land and ocean, to study the bidirectional reflectance properties of the Earth's surface and clouds, and to measure terrain topography and cloud heights. Images will be acquired at 443, 555, 670, and 865 nm with spatial sampling, selectable in-flight, ranging from 275 m to 1.1 km. This paper describes the rationale behind the instrument design and in-flight calibration approach, and discusses the application of MISR to the acquisition of global bidirectional reflectance measurements of the Earth.

## 1. Introduction

The NASA Earth Observing System (EOS) series of spacecraft comprises one component of the U.S. Global Change Research Program. The EOS-AM1 platform is scheduled for launch in June 1998. The spacecraft will be placed into a 16-day repeat 705-km Sun-synchronous orbit, with a local time at equator crossing of 10:30 am. The mission of EOS-AM 1 is to study the terrestrial surface, clouds, aerosols, and the Earth's radiation balance. One of the instruments to be carried as part of the payload is the Multi-angle imaging SpectroRadiometer (MISR), currently under development at the Jet Propulsion Laboratory. The MISR Science Team members are listed in Table 1.

MISR is being designed to provide multiple-angle, continuous imagery of the Earth in reflected sunlight. This observing strategy will enable MISR to make unique contributions to the EOS-AM1 mission objectives. Over cloud fields, MISR measurements will be used to investigate how spatial and seasonal variations of different cloud types affect the Earth's solar radiation budget. Another of the experiment's principal observational goals is to monitor global and regional trends in abundance and optical properties of aerosols in the Earth's troposphere. Aerosol information derived from MISR will also be used in the atmospheric correction of MISR surface imagery. Multi-angle surface images will aid studies of the impact of land processes on climate variables. For vegetated terrain, measured angular signatures will be related to canopy structural parameters, thus providing improved vegetation cover classifications. Retrieved surface hemispherical albedos will yield improved measures of vegetation canopy photosynthesis and transpiration rates. The multi-angle observations will also provide information necessary to interpret directional vegetation indices acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS), which will also be flying aboard the EOS-AM1 spacecraft.

Table 1: MISR Science Team

| Name | **Affiliation** |
|---|---|
| **David J. Diner** | Jet Propulsion Laboratory |
| Thomas P. Ackerman | **Penn. State University** |
| **Carol J. Bruegge** | **Jet Propulsion Laboratory** |
| **Roger Davies** | McGill University |
| **Siegfried A. W. Gerstl** | Los Alamos National Lab. |
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## 2. Instrument Overview

MISR will use nine separate charge coupled device (CCD)-based pushbroom cameras to observe the Earth at nine discrete angles: one at nadir, plus eight other symmetrically placed cameras that provide fore-aft observations with view angles, at the Earth's surface, of 26.1°, 45.6°, 60.0°, and 70.5° relative to the local vertical. The off-nadir cameras will use four unique, optical designs (designated "A", "B", "C", and "D" in order of increasing view angle followed by the letter 'f' or "a" to indicate forward or aftward viewing) to enable maintaining a pixel sample spacing in the crosstrack direction of 275 m at all angles. The nadir camera also makes use of the "A" design, and is designated "An". This provides slightly higher resolution in the nadir (250-m sample spacing). Provision for both forward and aftward views yields wide coverage in scattering angle (the angle between the direction to the observer and the solar illumination direction). It takes about 7 minutes to view any point on the sub-spacecraft track at all nine angles. The rationale for the camera selection is shown in Table 2. Note that although this table identifies each camera with a particular application for which observing at that angle is necessary, the cameras actually work together as a synergistic set to meet the experiment objectives. A unique feature of the MISR approach, in which a separate camera is dedicated to a selected set of view angles, is that multi-angle imagery is acquired on a continuous, global basis. This is in contrast 10 instrument designs using tiltable cameras, which require, reorientation of the sensor as the platform traverses overhead. In these cases, multi-angle imagery can only be acquired over selected targets separated by unobserved gaps, images in all four bands of all nine cameras of selected Earth targets by inhibiting pixel averaging in all bands of each of the cameras in sequence, one at a time, beginning with the first camera to acquire the target ("Df") and ending with the last camera 10 view the target ("Da"). This sequencing is referred to as Local Mode.

Table 2: Science rationale for the nine MISR cameras

| Camera | Rationale |
|---|---|
| **An** | Reference for image geolocation, minimally distorted by pointing errors and topography |
| **Af, Aa** | Stereoscopic cloud anti surface elevation retrieval |
| Bf, Ba | Intermediate angle for surface/cloud bidirectional reflectance and albedo determination |
| Cf, Ca | Aerosol retrieval and hemispherical albedo |
| Df, Da | Aerosol retrieval/cirrus cloud sensitivity |

MISR images at each angle will be obtained in four spectral bands centered at 443, 555, 670, and 865 am. The band selection is driven by requirements on vegetation identification and aerosol propert y retrieval. For example, the nearly factor of two difference in wavelength between the blue and near-infrared bands provides constraints on aerosol particle size. Also, the red and near-infrared bands are commonly used to identify the presence of vegetation due 10 the absorption of chlorophyll in the red and high leaf reflectances in the near-infrared.

Each of the 36 instrument data channels (4 spectral bands x 9 cameras) is individually commandable to provide ground sampling of 275 m, 550 m, or 1.1 km. This is accomplished through the use of on-board pixel averaging. The swath width of the MISR imaging data is 360 km, providing global multi-angle coverage of the entire Earth in 9 days at the equator, and 2 days at the poles. Global coverage in a particular spectral band of one camera is provided by operating the corresponding signal chain continuously in a selected resolution mode. A particular allocation of averaging modes among the 36 channels is referred to as a camera configuration. Continuous operation in any camera configuration consistent with MISR's data rate and power allocation is referred to as Global Mode. The present baseline for Global Mode is to operate. all of the nadir channels plus the red channel in all of the off-nadir cameras with no averaging, and to use 4 sample x 4 line averaging (i.e., ].1 km pixels) in the remaining 24 channels. The instantaneous data rate of this configuration is 5,68 Mbps, including data packetization overhead. In addition to Global Mode, the instrument is capable of providing high resolution

### 3. Bidirectional Reflectance Measurements

Knowledge of the directional reflectance properties of natural scenes such as soil targets, vegetation canopies, or cloud fields will lead to improved scene identification and classification and potentially provide, through inversion of physical models, descriptions of the structural characteristics of the target, such as soil grain size, canopy leaf orientation, or geometry of broken cloud fields. A number of researchers are developing physical models of light scattering in order to relate their reflective properties at multiple view angles to the internal physical structure. Observations obtained by MISR will provide a global data set with which to further develop and apply such models.

in addition to using the angular shape of BRF's measured by MISR as an indicator of the physical structure of either a cloud field or a land surface cover, the angular reflectance measurements will also be used to estimate a quantity known as the directional hemispheric reflectance, or albedo. This is the amount of light reflected by a particular target into the upward hemisphere, normalized by the downward flux of radiation illuminating it, Because natural scenes reflect light anisotropically, single-view angle sensors are not capable or retrieving accurate. values of albedo, in the absence of information regarding the bidirectional reflectance properties. MISR improves upon this situation by acquiring data over many view directions. The calculation of top-of-atmosphere albedos, and Surface albedos corrected for atmospheric scattering effects, are planned for the global data set to be acquired by the MiSR instrument.

Quantitative use of MISR imagery for the study of the Earth's ecology and climate requires high fidelity radiometric performance and instrument stability. Considerable attention has been paid in design of the instrument to providing highly accurate absolute and relative (pixel-to-pixel, band-to-band, and angle-to-angle) radiometric calibrations. For radiometrically calibrated MISR images, the measured radiances at each view angle and in each spectral band can be written as the sum of three terms: (1) sunlight scattered within the atmosphere and reflected back to space without interacting with the surface (also known as the path radiance); (2) downwelling light, reflected by the surface, and transmitted through the atmosphere to space without further scattering; and (3) downwelling light, reflected by the surface and diffusely scattered to the sensor. The downwelling light at the surface, consists of sunlight directly transmitted through the atmosphere on the downward path, plus diffuse skylight. Multiple reflections of photons between the surface and atmosphere must also be included in the bookkeeping.

If the radiance measured by MISR is normalized by the radiance that would be observed if the Earth (including atmosphere) were replaced by a totally reflective lambertian surface, the resulting quantity is referred to as the top-of-atmosphere bidirectional reflectance factor, or BRF. The term "bidirectional" is used because there are two primary directions of the radiation: the solar incidence direction, and the view direction. In general, BRF's for natural scenes will depend on the zenith angles of both of these directions, as well as the azimuthal angle between the planes in which the view and illumination vectors occur.

Over optically thick cloud fields, most of the radiation observed by MISR comes from the clouds and very little surface radiation leaves the atmosphere. As a result, the MISR observations provide a direct measure of the cloud BRF's. On the other hand, for cloud-free scenes, the effects of atmospheric scattering (predominantly Rayleigh scattering due to air molecules and scattering by atmospheric particulates, or aerosols) must be taken into account, and atmospheric correction algorithms must be applied to MISR data in order to convert top-of-atmosphere BRF's to surface BRF's. On any given overpass, MISR observes a specific point at nine distinct view angle.s in a single azimuth angle plane. This set of measurements must be put into the radiative transfer equation which describes the. scattering processes enumerated above. The surface BRF enters into this equation in a complicated fashion, and an iterative procedure is required in order to retrieve it. (Main pieces of information, such as the reflective properties of the surface over a wide range of illumination angles, must be incorporated into the retrieval scheme because skylight illuminates the surface over an entire hemisphere (in contrast to direct sunlight, which is unidirectional). Since this information is not known *a priori* for a given surface, one of two approaches must be taken: (1) it must be assumed that the BRF is independent of illumination angle, or (2) a physical model of the surface BRF that describes the bidirectional reflectance properties in terms of a few free parameters must be adopted. Both of these approaches are currently being investigated for MISR.

## 4, Instrument Description

### Cameras

The MISR came.ras are of refractive design, and determination of the lens prescriptions has been completed. The first order properties of the four unique lens designs are shown in Table 3.

JPL has taken delivery of the glass blanks from which the lenses will be fabricated. The lenses will be mounted in a lens barrel that consists primarily of aluminum with some additional materials to accommodate thermally induced dimensional changes of the lenses during flight. In addition, each MISR camera contains a camera head which houses the focal plane structure and to which is attached the CCD driver electronics. The camera heads and electronics are identical for all nine cameras, leading to a modular design in which only the lens barrels are unique.

**Table 3: MISR optics first-order parameters**

| Camera design | Effective focal length (mm) | Field of view (deg) |
|---|---|---|
| A | 59.3 | ±14.9 |
| B | 73.4 | ±12.1 |
| C | 95.3 | ±9.4 |
| D | 123.8 | ±7.3 |

The use of multi-layer antireflection coatings for the lenses make.s the expected transmittance of the cameras about 80%. The lenses are superachromatic, 7-element f/5.5 telecentric designs, in which the chief rays exit the cameras nearly normal to the optical axis independent of location in the field of view, with the benefit that bandpass of the focal plane interference filters is nearly constant across the field. In addition, optical transmittance is only a weak function of field angle. Because the telecentric design has unequal transmittance for off-axis light in different linear polarization states, a double plate Lyot depolarizer is incorporated into each of the cameras in order to scramble the polarization state. The effectiveness of Lyot depolarizers is dependent on the spectral bandwidth as well as the spectral band shape. The MISR filters are specified to have gaussian-like band shape profiles in order to optimize the depolarizer performance.

### Focal Plane

The MISR CCD architecture consists of four line arrays (one for each spectral band) on a common piece of silicon. The center-to-center spacing is 160 pm. There are 1504 active pixels per line, and the pixels are 21 μm square. Full well capacity exceeds 800,000 electrons with read noise less than 20 electrons, yielding a large dynamic range for the devices. Integration time for each line array can be controlled independently using a separate electronic shutter and output amplifier. This allows for different integration times in different bandpasses in order to equalize radiometric performance and maximize signal-to-noise ratio. The arrays are read out with a 40.8 msec line repeat time. To minimize dark current and radiation sensitivity, the CCD's will be operated at -20°C. Temperature control is accomplished with a single stage Thermo-Electric Cooler (TEC) in each focal plane. The TEC's are always on and small amounts of heat are added to control the temperature to ±0.1°C. The amount of heat is controlled by the instrument computer in a digital control loop. All TEC's (9 total, one for each camera) are powered by the. system power supply and placed in series. A diode is placed in parallel with each TEC such that a single TEC failure does not disable the entire string. The heat generated by the TEC's are conducted through solid rods to a nadir-facing radiator.

MISR CCD's are being manufactured by Loral Fairchild imaging Systems. The CCD architecture is based on standard 3-phase, 3-poly, n-buried channel silicon detector technology. Additional processing is performed to create a "thin-poly" CCD. For this device, the third poly deposition over the, photogate (active pixel) region is etched down. This is followed by deposition of a thin fourth poly layer. This etching and deposition process for the thin-poly device is necessary to insure that the poly layer thinning occurs over the photogate region only and to maintain continuous electrical contact throughout the entire line array. The thickness of the poly gate over the active pixels is about 400 A, as compared to 2000 A for the more conventional "thick-poly" devices. The thin-poly CCD is a new technology developed to increase the detectors' sensitivity in the blue spectral region.

A focal plane filter defining the four optical bandpasses is placed directly over and in contact with the CCD. The MISR filters will be manufactured by Barr Associates, Inc. The camera filters are an array of four separate medium band filters patterned on a single substrate such that when the. filters are installed into the CCD package each of the four CCD line arrays will see a different color. The filter specifications require a high degree of uniformity among all filters, as well as very stable and durable. coatings which will not shift or degrade with age or environmental stresses. The filters will utilize a sandwich design with all of the spectral coatings on the interior of the filter with anti-reflection coatings on both exterior surfaces.

**Camera and System Electronics**

Each of the nine MISR cameras has its own power supply and serial data interfaces. The power supplies are 25 kHz sine wave supplies, which combine high efficiency (72%) with low noise performance. The camera electronics can stand alone through most testing and camera calibration. The camera digital electronics provide interfaces to the system electronics controlling the camera as well as all the drive and timing signals to the CCD, the signal chain, and engineering signal conditioning (ESC) circuits. The signal chain amplifies and converts the CCD video into 14 bit digital numbers. The 14-bit data numbers output from the analog-to-digital converters are then square-root encoded to 12 bits prior to data packetization. There are four signal chains per focal plane for a total of 36 in the instrument. The signal chains are hybrids, providing both noise and mass advantages. All camera digital circuits will reside on Field Programmable Gate Arrays (FPGA's).

The system digital electronics provides an interface between the instrument and the spacecraft. All system electronics is redundant such that a single point failure can occur and the instrument will continue to function. The system electronics contains redundant 17SOA computers with 1553-bus interfaces to the spacecraft. All commands from the spacecraft and engineering data go through the 1553-bus. The system electronics also provide the high speed data interface, control inputs to the cameras, control power throughout the instrument, and control all of the mechanisms. A system ESC circuit measures system-wide temperatures and voltages. As in the cameras, all of the custom digital circuits will reside on FPGA's.

**Structural Design**

The MISR instrument configuration includes the following subassemblies: base frame, enclosure, and optical bench.

The optical bench holds the nine cameras at their front end (i.e., the end at which light enters the cameras) with the detector end cantilevered into the instrument cavity. The fore-aft cameras are paired in a symmetrical arrangement and set at fixed view angles on the optical bench. Light baffles are mounted to the optical bench in front of each camera to protect the optics from incident sunlight during the period that Earth observations are being acquired. Thermal blanketing surrounds each camera to prevent thermal coupling between the cameras and the electronics inside the instrument cavity. In addition to the nine cameras, the optical bench contains the on-board calibration hardware, which is described in the next section.

The base frame provides kinematic attachment to the spacecraft bus and is designed to maintain rigid support for the optical bench. The instrument enclosure provides a structural mount for the radiators located on the nadir-facing side of the. instrument. In addition, it houses the optical bench assembly, the instrument system electronics, and the flight computer.

Earlier designs of the MISR instrument contained passive thermal radiators on both the nadir and sun-facing sides of the instrument. However, subsequent analyses showed that requirements on thermal stability of the instrument could not be met in a simple fashion with those designs due to thermal cycling resulting from variable amounts of sunlight on the sun-facing radiator as the instrument transitioned in and out of darkness during each orbit. The current design relies solely on nadir radiators allocated to the TEC's and to the other electronics. Thermal analyses indicate that the current approach meets the design requirements on thermal stability.

## 5. Radiometric Calibration

Accurate determination of top-of-atmosphere and surface bidirectional reflectances with MISR necessitates the imposition of stringent absolute and relative radiometric calibration requirements on the instrument. These requirements, specified at the 68% confidence level, are shown in Table 4.

**Table 4: Radiometric performance requirements**

| Equivalent reflectance | Maximum radiometric uncertainty | Maximum camera-to-camera radiometric uncertainly |
|---|---|---|
| 100% | ±3% | ±1% |
| 5% | ±6% | ±2% |

The performance requirements are defined at signal levels expressed as equivalent reflectances, defined as:

$$P_{equiv} = \pi L_{\lambda}/E_{0\lambda}$$

where $L_{\lambda}$ is the spectral radiance incident at the sensor while observing a given target, and $E_{0\lambda}$ is the spectral exo-atmospheric solar irradiance at wavelength λ. The use of equivalent reflectance permits the radiance levels at which radiometric requirements are specified in all spectral bands to be expressed in terms of a single band-independent parameter. Meeting the performance requirements shown in Table 4 requires the instrument to be radiometrically calibrated in order to insure that the requirements are met over the lifetime of the experiment. The absolute radiometric performance requirement allows the determination of changes in the solar radiation budget to accuracies required for climatology studies, while the camera-to-camera requirement insures that the angular variation of top-of-atmosphere bidirectional reflectances can be determined to high accuracy.

Because both absolute radiometric accuracy as well as angle-to-angle accuracy are important to the MISR experiment, specialized hardware has been incorporated into the instrument design. Among the primary elements of the MISR On-Board Calibrator (OBC) are two calibration plates containing diffusely reflecting panels of Spectralon, a high reflectance, nearly lambertian material manufactured by Labsphere, Inc. The two symmetrical calibration plate devices will be assembled on a single mounting interface that fastens to the optical bench on the sun-facing side of the instrument. MISR will be recalibrated, in-flight, at approximately monthly intervals, using observations acquired when the spacecraft is near each of the poles. During calibration near the North pole, a panel is deployed into a position in which it can be viewed by the aftward-looking and nadir cameras. Sunlight is reflected from the diffuse panel, and illuminates each camera with near-equal radiances. Near the South pole, the other panel, which is viewed by the forward-looking cameras, is deployed. This panel is also observed by the nadir camera to provide a link between the two sets of observations.

MISR has provided for the flight qualification of Spectralon. Areas of investigation for flight qualification include static-charge build-up studies, optical characterization, environmental exposure (including UV, humidity, atomic oxygen and thermal cycling impact studies), measurement of mechanical properties such as tension and compression strengths, and vibration testing. In designing the containing tray for the calibration targets, consideration has been given to the softness, thermal expansion characteristics, and required thickness of Spectralon. During handling, assembly, and storage of the panels, witness samples will be utilized. These will provide verification that the panels have not been contaminated prior to launch. Because contamination is a concern, the panels will be carried solely in metal or glass containers. Should contamination occur, the material can be cleaned using a vacuum-bake procedure developed and tested at JPL.

In order to monitor the reflectance characteristics of the Spectralon during the course of the EOS mission, the OBC contains four stationary packages of radiation resistant photodiodes, two facing the nadir and two aligned with the "D" cameras; four high quantum efficiency (HQE) diode packages; and the goniometer, a modular assembly containing an actuated radiation resistant diode package, on a swinging arm to view the diffuse calibration plates over a range of view angles. The goniometer mechanism attaches to the opposite end of the optical bench as the mounting interface for the calibration plates. Calibration electronics include diode pre-amplifiers and ESC circuits associated with the diodes.

## 6. Conclusion

The Preliminary Design Review for the MISR instrument was held in May 1993. An Engineering Model (EM) of the MISR instrument will be fabricated during 1994. The EM will differ from the flight instrument in that it will contain only two cameras (one each of the "A" and "D" designs) and commercial parts will be used for many of the electronic components. A Critical Design Review of the MISR instrument will be held late in 1994 and fabrication of the flight instrument will occur in 1995. Pre-flight calibration of the MISR cameras will occur prior to their integration into the instrument system. Delivery of the assembled flight unit to the EOS-AM1 platform manufacturer, Martin Marietta, is scheduled for February 1997.

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